

Energy Consumption Estimation for Room Air-conditioners Using Room Temperature Simulation with One-Minute Intervals

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Abstract: For the purpose of developing optimized control algorithm for room air-conditioners to ensure their energy efficiency, a short time interval (i.e., one minute) simulation of building thermal performance is necessary because the sampling time interval for room air-conditioner control is one minute in general. This paper studies the short-time interval room air temperature simulation method using the response factor method. Using the simulated room air temperature, an air-conditioner's running time can be known so that its energy consumption can be estimated accurately. In order to verify the simulation accuracy, an actual room equipped with a gas-engine heat pump (GHP) air-conditioning system is studied by both simulation and measurement. The cooling amount produced by the GHP is calculated using measured refrigerant pressure and temperature at condenser and evaporator respectively. The Root Mean Square Error (RMSE) between measured cooling amount and simulated cooling load is 18.9 percent of the average measured value. The profile of simulated room air temperature in both air-conditioned daytime and nighttime without air-conditioning can match the measured room air temperature. With respect to the estimated energy consumption, the profile of simulated energy consumption can match the measured data. The simulation accuracy of room air temperature and energy consumption during the air-conditioner start-up period is not good and needs to be improved in future research. But in general, the verification shows that this energy consumption simulation method is acceptable for evaluating the energy performance of a room air-conditioner, and can also be a useful tool for commissioning room air-conditioners.

Key words: Energy Consumption, Room

Air-conditioner, Simulation, Commissioning

1. INTRODUCTION

The energy efficiency of buildings' Heating, Ventilating and Air-Conditioning (HVAC) system is an important issue because approximately one third of primary energy is consumed in non-industrial buildings such as dwellings, offices, hospitals, and schools where it is used for space heating and cooling, lighting and the operation of appliances ^[1]. The energy efficiency of HVAC system devotes to both energy saving and reducing carbon dioxide discharge, which is considered to be one of the main reasons for global warming. Therefore the energy efficiency of HVAC systems is studied at a lot of respects, such as isolation of building envelopes, free cooling by natural ventilation, optimizing the operation of HVAC systems, commissioning for HVAC systems, etc. With respect to room air-conditioner, high Coefficient Of Performance (COP) air-conditioners are increasing and optimization of the air-conditioner control algorithm is also a focus of air-conditioner manufacturers.

However the newly developed air-conditioner control algorithm has to be verified through a year-round operation at different types of buildings, which takes too much time and cost. Simulating the thermal performance of an air-conditioner controlled by the newly developed control algorithm considering the thermal performance of the building where the air-conditioner is installed is a viable way that can verify the performance of the control algorithm but do not take much time and cost. However most of now available building thermal performance simulation methods are one-hour interval, which does not match the control time

interval of room air-conditioners. Therefore a short-time interval (typically one-minute) building thermal performance simulation method considering the thermal performance of room air-conditioners is developed to simulate the room air temperature in short time interval and use the temperature simulation results to estimate the energy consumption of the air-conditioners in the building. Using the simulated room air temperature, an air-conditioner's running time can be known so that its energy consumption can be estimated accurately. Then the simulation accuracy is verified using an actual room equipped with a Gas-engine Heat Pump (GHP) air-conditioning system through comparing the simulation results with measured data.

2. SIMULATION METHOD

The short time interval building thermal performance simulation method proposed here uses response factors to the triangle temperature excitation. As shown in Figure 1, if there is a 1°C temperature excitation (the temperature difference between air at the two opposite sides of a wall) exerted on a wall from time $t = -1$ to 1 , the thermal response of the wall, the heat transfers φ_T between the air at the two opposite sides of the wall and the heat absorptions at the surface of the wall φ_A at time step $t = 0, 1, 2, \dots$ are $\varphi_{T0}, \varphi_{T1}, \varphi_{T2}, \dots$ and $\varphi_{A0}, \varphi_{A1}, \varphi_{A2}, \dots$ respectively. Using these response factors, the heat transfer and heat absorption can be calculate using convolution integral method by summing up all the product of the temperature excitations and the response factors corresponding to them at all the past time steps, as shown in Equation 1 and 2.

Therefore, if the heat flowing into the room air from the inner surface of all the room envelopes and

internal heat source can be calculated, the room temperature change can be obtained using Equation 2. The room air temperature calculation method is described in detail in the following parts.

$$q_T = \sum_{n=0}^{\infty} \varphi_{T,n} \theta_{t-n\Delta t} \quad (1)$$

$$q_A = \sum_{n=0}^{\infty} \varphi_{A,n} \theta_{t-n\Delta t} \quad (2)$$

Where,

q_T : Heat transfer through building envelopes, (W/m^2)

q_A : Heat absorption at the surface of a building envelope, (W/m^2)

n : Time step

t : Current time

$\varphi_{T,n}$: Heat transfer response factor at time step n , ($\text{W/m}^2 \cdot ^\circ\text{C}$)

$\varphi_{A,n}$: Heat absorption response factor at time step n , ($\text{W/m}^2 \cdot ^\circ\text{C}$)

θ_t : Temperature excitation at time t , ($^\circ\text{C}$)

Δt : Time step interval, (hour or minute, etc.)

2.1 Room Air Temperature T_i

For a room with air temperature of T_b , if heat Q_i flows into room air, air temperature will increase to T_i . In another word, if room air temperature increases form T_b to T_i , the heat of Q_i will be absorbed by the

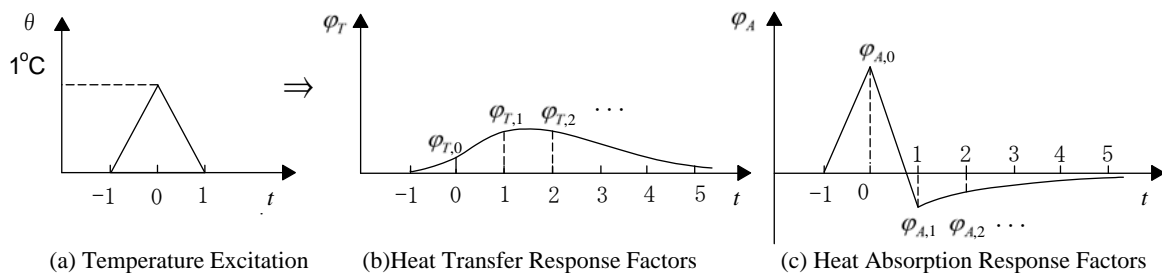


Fig 1. Response Factors to Temperature Excitation

surface of room elements, such as walls, floors, roofs, furniture etc. Therefore the room air temperature can be calculated using Equation 3.

$$T_i = \frac{Q_i}{\psi_1} + T_b \quad (3)$$

Where,

Q_i : Heat flowing into the room air, (W)

T_i : Room air temperature at time step i , ($^{\circ}\text{C}$)

T_b : Base room air temperature at time step i , ($^{\circ}\text{C}$), used to calculate the temperature excitation ($\theta = T - T_b$). Generally the air-conditioning set point is used as a base temperature.

ψ_1 : The first heat absorption response factor of all room elements, ($\text{W}/^{\circ}\text{C}$)

The following parts describes the detailed calculation method for Q_i and ψ_1 .

2.2 Heat flow Q_i

The heat Q_i flowing into the room air consists of three parts: heat transferred through building envelopes and indoor heat generation $Q_{g,i}$, heat flow caused by furniture's thermal storage $Q_{s,i}$, and heat processed by room air-conditioners $Q_{AC,i}$, as shown in Equation 4.

$$Q_i = Q_{g,i} + Q_{s,i} + Q_{AC,i} \quad (4)$$

(1) Heat transferred through building envelopes and indoor heat generation $Q_{g,i}$

Because generally only the one hour interval weather data are available, the short time interval heat transferred through building envelopes and indoor heat generation $Q_{g,i}$ is calculated through interpolation of one hour interval heat, as shown in Figure 2. The following parts will use one minute interval, the typical air-conditioner control sampling interval, as an example to discuss the short time

interval simulation method. Equation 5 shows the interpolation method for calculating one minute interval heat transferred through building envelopes and indoor heat generation $Q_{g,i}$.

$$Q_{g,i} = Q_{g,h} + \frac{Q_{g,h+1} - Q_{g,h}}{60} i \quad (5)$$

Where,

$Q_{g,h}$: Heat transferred through building

envelopes and indoor heat generation at time step of h hour, (W)

i : The minute interval time step i

The heat transferred through building envelopes and indoor heat generation $Q_{g,h}$ consists of six parts: heat transferred through building envelopes, i.e. walls, roofs, and floors $Q_{e,h}$, heat transferred through window glasses $Q_{w,h}$, solar radiation heat penetrated through window glassed $Q_{r,h}$, heat generated by human beings in room $Q_{h,h}$, heat generated by lights and machines $Q_{lm,h}$, and heat caused by ventilation $Q_{v,h}$, as shown in Equation 6.



Fig. 2. Interpolation of Heat Transfer through Building Envelopes and Indoor Heat Generation

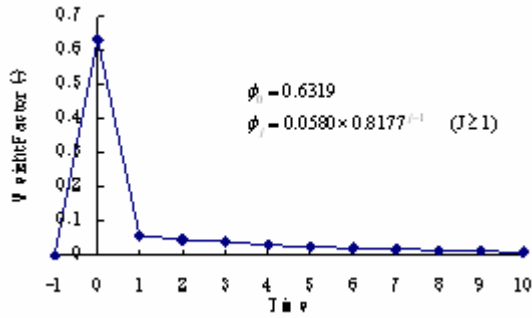


Fig. 3. Empirical Weight Factors for Calculating Cooling Load from Heat Transferred through

Because the heat gains do not become cooling load immediately for the radiation part of heat flows into air after it is absorbed by envelopes and furniture, all the heats flowing in indoor air are calculated using convolution integral of the heat gain G and load weight factor w , as shown in Equation 7. An example for typical weight factors for heat gain from wall is shown in Figure 3.

Heat gain from building envelopes G_e can be calculated using convolution integral of the heat transfer response factors ϕ_T and temperature excitations θ , as shown in Equation 1. Heat gain from transferring through window glasses G_w is calculated using constant heat transfer calculation method, as shown in Equation 8, because the thermal capacity of glass is so small that it is safe to ignore its influence to the heat transfer calculation. Heat gain from occupants G_h is calculated using human heat generation at different room air temperature and different work level. Heat gain from lightings and machines G_{lm} is calculated using their rated power consumptions. Because heat gain from ventilation flows into indoor air directly, ventilation heat flow Q_v is calculated by multiplying the ventilation air volume flow rate by the enthalpy difference between indoor and outdoor air and the weight factors are not used.

$$Q_{g,h} = Q_{e,h} + Q_{w,h} + Q_{r,h} + Q_{h,h} + Q_{lm,h} + Q_{v,h} \quad (6)$$

$$Q = \sum_{n=0}^{24} w_n G_{t-n} \quad (7)$$

Where,

Q : Heat flowing into indoor air, (W)

w_n : Cooling load weight factor at time step n

G_t : Heat gain at t hour, (W)

$$G_{w,h} = A_w K_w (T_{o,h} - T_{i,h}) \quad (8)$$

Where,

A_w : Window area, (m^2)

K_w : Window heat transfer coefficient, ($W/m^2 \cdot ^\circ C$)

$T_{o,h}$: Outdoor air temperature at h hour, ($^\circ C$)

$T_{i,h}$: Indoor air temperature at h hour, ($^\circ C$)

(2) Heat flow from furniture thermal storage $Q_{s,i}$

The heat flowing in air caused by the thermal storage of walls and furniture is calculated using the convolution integral of room temperature excitation θ at all the past time steps and the corresponding heat absorption response factors of all room elements ψ , as shown in Equation 9. As shown in Figure 1, the response factor curve after a certain time step N , for example 10 hours, is very near a linear curve. Therefore the response factors after the time step N can be approximated using a geometrical series with a rate of r_a . Accordingly, the infinite series shown in Equation 9 can be approximately described using a finite series that is convenient for computer calculation, as shown in Equation 10.

$$Q_{s,i} = \sum_{n=0}^{\infty} -\theta_{i-n} \psi_n \quad (9)$$

$$Q_{s,i} = \sum_{n=1}^N -\theta_{i-n} \psi_n + Q'_{s,i} \quad (10)$$

$$Q'_{s,i} = r_a Q'_{s,i-1} - \theta_{i-(N+1)} \psi_{N+1}$$

Where,

$Q_{s,i}$: Heat flow caused by the thermal storage of

walls and furniture at time step i , (W)

θ_i : Temperature excitation (difference between room air temperature and base temperature) at time step i , ($^\circ C$)

ψ_n : Absorption response factor of all room elements for the temperature excitation of n time steps before, ($W/^\circ C$)

(3) Heat processed by room air-conditioners $Q_{s,i}$

If at present time step the air-conditioner is working, the approximate value of the heat processed by the air-conditioner $Q_{s,i}$ is counted using the nominal cooling capacity of the air-conditioners. If the air-conditioner is idling, the heat processed by the air-conditioner $Q_{s,i}$ is assumed to be zero. Whether the air-conditioner is working or idling can be determined according to control algorithm. When an air-conditioner is working, the room air temperature will decrease gradually. The air-conditioner will work until the room air temperature reaches the lower temperature limit determined by the control algorithm. On the contrary, when the air-conditioner is idling, the room air temperature will increase gradually until the temperature reaches the upper limit and then the controller will turn the air-conditioner from idling to work.

The following part describes the calculation for response factors

2.3. Response factor ψ_i

The heat transfer and absorption response factors are determined using the discrete Fourier transform for triangle excitation shown in Figure 1-a and the thermal parameters, such as thermal capacity, heat conductivity, etc., of the every layer of the

multiplayer building envelopes [2]. After the building envelopes response factors are determined, the response factors of all room elements can be calculated by summing up the product of the response factors and the corresponding envelope area, as shown in Equation 11. Because in every time step interval, the room air temperature is assumed to be same, the heat used to change the room air temperature is considered by adding the product of air specific heat capacity and room volume to the room response factors, as shown the second term in Equation 11.

$$\psi_n = \sum_{k=1}^m \varphi_{k,n} A_k + C_a V \quad (11)$$

Where,

A_k : Area of the building element of No. k , (m^2)

C_a : Air specific heat capacity, ($kJ/m^3 \cdot ^\circ C$)

V : Room volume, (m^3)

$\varphi_{k,n}$: Absorption response factor of room

element of No. k for the temperature excitation of n time steps before, ($W/m^2 \cdot ^\circ C$)

ψ_n : Absorption response factor of all room elements for the temperature excitation of n time steps before, ($W/^\circ C$)

An example of heat absorption response factor of a wall and the response factors of a room is shown in Figure 4. The left drawing in Figure 4 shows the heat absorption response factors of unit wall area. The right drawing in Figure 4 shows the room response factor calculated by summing up the product of the envelope response factors and the corresponding envelope area.

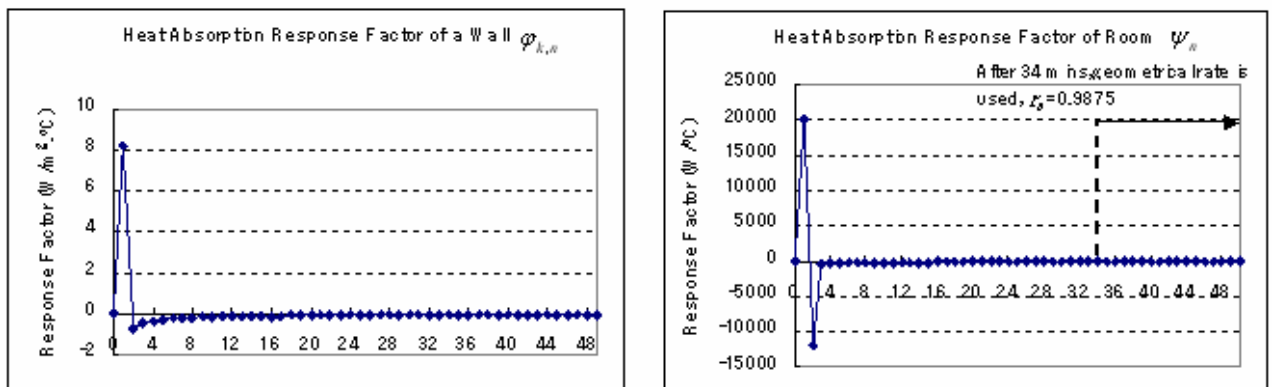


Fig. 4. An Example of the Heat Absorption Factors of a Wall and Room

Besides the room envelopes, the furniture in room also absorbs and discharges heat so that the furniture heat capacity has to be considered when calculating the room response factor. For the traditional one hour interval simulation, an empirical value, which is ten times of the air heat capacity, is used for simulation. However, for one minute interval simulation, this empirical value is not proper. In this paper, the furniture heat storage effect is considered by assuming it to be indoor wall of 30 mm wood board that has the same surface area as furniture.

2.4 Energy Consumption

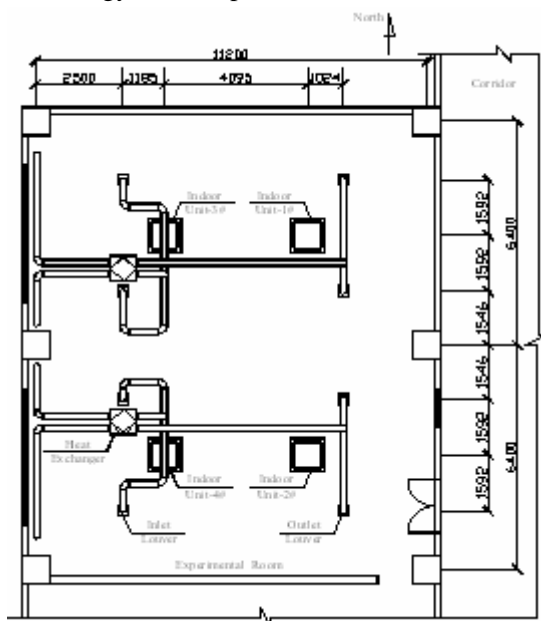


Fig. 5. Plan of the Room for Simulation and Measurement

Using the room air temperature simulation results, at every time step whether an air-conditioner is working or not can be determined. Then the energy consumption of the air-conditioner can be calculated using the data that influence the energy consumption. In general, the data influencing the air-conditioner energy consumption are indoor air temperature, outdoor air temperature, and cooling amount produce by the air-conditioner, which can be determined using the simulated cooling load. From air-conditioner manufacturers' specification data, the energy consumption model of room air-conditioners can be developed. As an example, Equation 12 shows an air-conditioner model developed by the authors using a manufacturers specification data [3]. The reference 3

describes the details, the validation and the application of the model.

$$E_r = (a_1 T_o^2 + a_2 T_o + a_3)(b_1 T_i^2 + b_2 T_i + b_3)(c_1 CA^2 + c_2 CA + c_3) + d \quad (12)$$

Where,

E_r : Ratio of Energy consumption to rated energy consumption

$a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3, d$: Coefficients

CA : Cooling amount produced by air-conditioner, (kW)

T_i : Indoor air wet-bulb temperature, ($^{\circ}\text{C}$)

T_o : Outdoor air dry-bulb temperature, ($^{\circ}\text{C}$)

Tab. 1. Profile of the Air-conditioner for Experiment

Place	R&D Center, Yanmar Co. LTD.
Air-conditioner type	GHP YNZP355F1
Heating/cooling capacity (kW)	42.5/35.5
Rated LPG consumption (heating/cooling, kW) (LPG HHV=90.27MJ/Nm ³)	28.0/28.5
Refrigerant	R407C
Outdoor unit rated power (kW)	1.09
Outdoor unit fan rated air flow rate (m ³ /min)	230
Indoor unit number	4
Indoor unit rated power (W)	30
Indoor unit fan rated air flow rate (high/low speed, m ³ /min)	20/15

3. SIMULATION VERIFICATION

In order to check the accuracy of the former mentioned simulation method, an office room in the research center of Yanmar Co. LTD. in Japan was used for simulation and measurement. The plan of the room is shown in Figure 5. The room is equipped with a multi-split type Gas Heat Pump (GHP) air-conditioner fired by Liquefied Petroleum Gas (LPG) and two heat recovery systems for recovering

ventilation air energy. The profile of the air-conditioner is shown in Table 1. The detailed data of the room, such as structure of walls, floors, roof, ceiling, occupant number, lighting and machine power etc., were used to construct the building model for simulation. The followings show the comparison of simulated cooling load, room air temperature and energy consumption to the measured data.

3.1 Verification of the Accuracy of Cooling Load Simulation

For the purpose of checking the accuracy of cooling load simulation, the cooling amount produced by the air-conditioner is calculated using the flow rate and enthalpy of refrigerant at condenser and evaporator. The refrigerant property calculation software REFPROP^[4] is used to calculate the refrigerant density and enthalpy given refrigerant composing substance, and refrigerant pressure and temperature at the condenser and evaporator. The refrigerant flow rate, pressure and temperature are measured using pipe insert type sensor and recorded automatically using data logger. The comparison of simulated cooling load to the measured data is shown in Figure 6. The root mean square error (RMSE) is 18.9% of the average measured data. The accuracy is acceptable for using the simulated cooling load to calculate energy consumption.

3.2 Verification of the Accuracy of Room Air Temperature Simulation

Using the simulated cooling load, room air temperature can be simulated using Equation 3. The simulated room air temperatures are compared with measure data as shown in Figure 7. From Figure 7, it can be seen that during night when air-conditioner stops, the simulated room air temperature can match measured temperature quit well. During the period when air-conditioner starts up, the simulated running time of air-conditioner is about two hours. While from the measured air temperature, the continuous running time at start up is about one hour. The reason for this difference might be that the method for considering the thermal capacity of furniture is not proper. In the future research, this issue will be studied in detail.

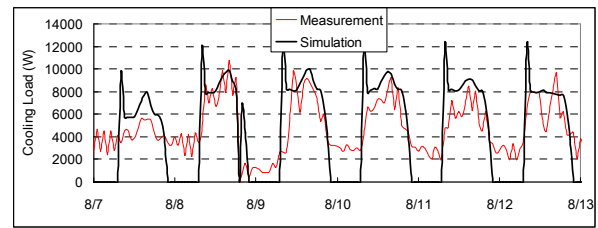


Fig. 6. Comparison of Simulated and Measured Cooling Loads

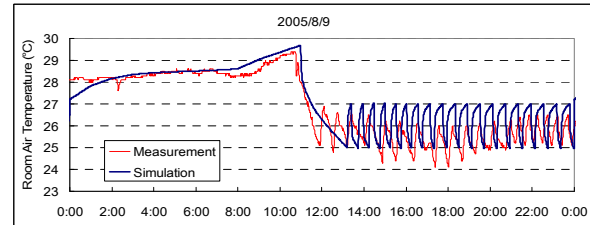


Fig. 7. Comparison of Simulated and Measured

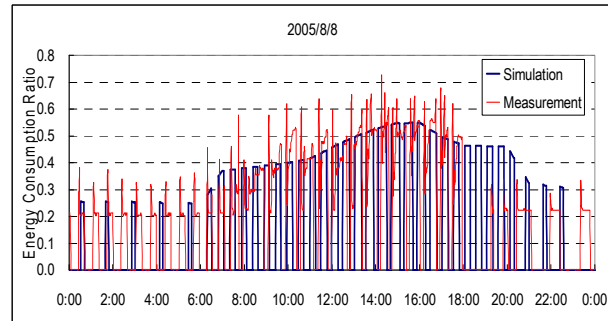


Fig.8. Comparison of Simulated and Measured Energy Consumption Ratio

Tab.2. Coefficients of GHP Energy Consumption Model

a_1	3.8841358e-004;
a_2	4.7352327e-0032;
a_3	6.9612680e-001;
b_1	2.8466614e-004;
b_2	-1.2641405e-002;
b_3	3.8456041e-001;
c_1	2.0340157e-004;
c_2	7.5236245e-002;
c_3	-5.5769396e-001;
d	2.2280461e-001;

In the period when air-conditioner is switched on, the simulated room air temperature profile can match the measured one. This shows that the simulated room air temperature can be used to determine the

working status of air-conditioner and to calculate its energy consumption in detail.

3.3 Verification of the Accuracy of Energy Consumption Simulation

The energy consumption model coefficients shown in Equation 12 are fitted using manufacturer's specification data. The coefficients fitting results are shown in Table 2. Then the energy consumption of air conditioner is calculate using Equation 12, simulated room air temperature, measure outdoor air temperature, simulated cooling load, and the working status of air-conditioner determined from simulated room air temperature. The calculated energy consumptions are compared with measured ones, as shown in Figure 8. From this figure, it can be said that the simulated energy consumptions can approximately match the measure value

However, from Figure 8 it can be found that the measured energy consumption has a spike at the time when air-conditioner turns its status from idling to working. This phenomenon was not reproduced by simulation. To simulate this phenomenon and to improve the simulation accuracy, the dynamic energy consumption model is necessary, which is a theme for the future research.

4. SIMULATION TOOL

A simulink[®]-based simulation tool is developed using the former described simulation method. The tool can make the simulation user-friendly through graphic user interface, as shown in Figure 9. Through this interface, user can specify the simulation period, start, pause or stop the simulation. The simulation results are visualized online, as shown in Figure 10. On the visualization window, user can check the curve of simulated room air temperature, cooling load, energy consumption and the status of the air-conditioner working or idling.

5.CONCLUSIONS

This paper proposes a method to simulate the room air temperature and energy consumption of air-conditioners in short time interval, typically one-minute for the purpose of check the performance of air-conditioner and air-conditioner control

algorithm, which is generally uses one-minute sampling interval for control.

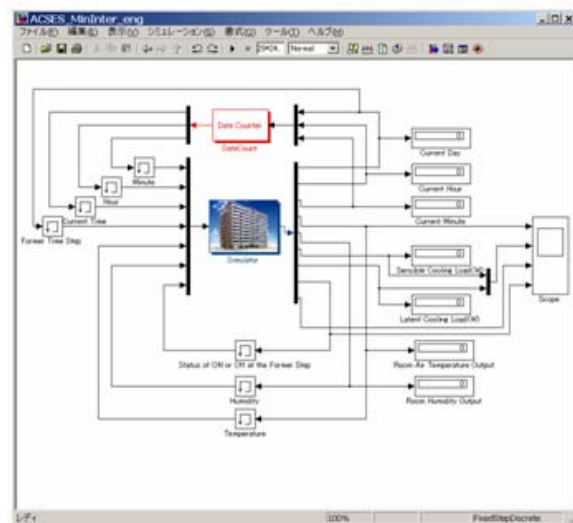


Fig. 9. User Interface for Simulation

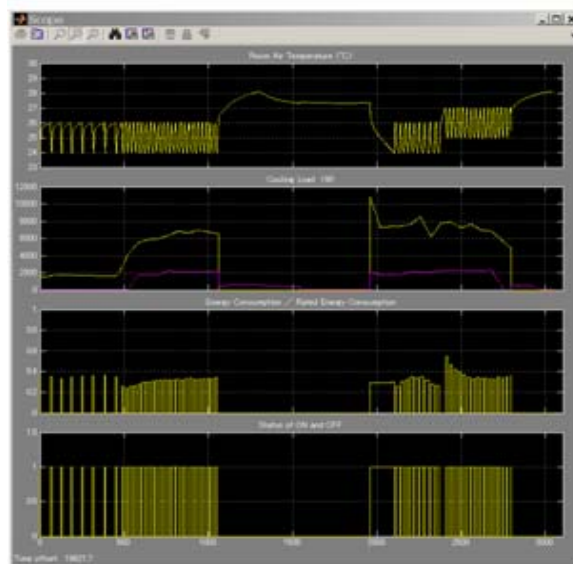


Fig.10. Visualization of Simulation Results

In order to check the accuracy of the simulation, the simulation was conducted for an existing office room and simulation results are compared with measurement data. The RMSE between measured cooling amount and simulated cooling load is 18.9% of the average measured value. The simulation for room air temperature in nighttime without air-conditioning can match the measured room air temperature well. The simulated room air temperature in the daytime with air-conditioning can reproduce the behavior of room air temperature, which is shown by comparing the profile and frequency of temperature increasing and decreasing to the measurement. With respect to the estimated energy consumption, the profile of simulated energy

consumption can match the measurement. However, the simulation accuracy of room air temperature during the period of air-conditioner starting up is not good. The simulated temperature decreasing time is twice of measurement. This needs to be solved in future research. But in general, the verification shows that this room air temperature and energy consumption simulation method is acceptable to use it for evaluating the energy performance of a room air-conditioner and the control algorithm. Furthermore a simulation tool using the method proposed here is developed, which can be a useful tool for commissioning room air-conditioners.

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